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Comparison of LS-PWM with Different Modulation Strategies for SVC PLUS

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Abstract

Urbanization is continuing around the world accompanied by a constantly growing demand for energy. For these reasons, new and efficient solutions for power transmission are required. To cope with these new challenges a novel SVC PLUS (Static Var Compensation SVC) for Reactive Power Compensation is designed and researched. SVC PLUS is an advanced STATCOM (Static Synchronous Compensator) with Modular Multilevel Converter (MMC) technology, also called (M-STATCOM). In this paper the M-STATCOM is simulated in PSCAD environment with 100 sub-modules per phase. Its static and dynamic characteristics are discussed. After compare and contrast different modulation schemes, harmonic contents in Level-shift sine pulse width modulation (LS-PWM) are found having least total harmonic distortions (THD) and with this modulation scheme converter can achieve more levels so it is found feasible to control the converter. The behaviour of circulating current with least ripples is also observed. In this paper, the traditional capacitor balance strategy is also modified.The viability of the MMCs as well as the effectiveness of the LS-PWM control method is confirmed by simulation.

Keywords: *SVC PLUS (Static Var Compensation SVC), LS-PWM modulation strategy, the circulating current*

1. Introduction

Reactive power compensation based on thyristor controlled technology started in the mid 1970s and has achieved a high degree of maturity in many applications, worldwide.SVC PLUS [1] is an innovative and universally applicable solution for grid enhancement. SVC PLUS offers convincing advantages in all respects:

a) Improved dynamic stability
b) Increased power quality
c) Highly efficient flicker reduction in industrial applications
d) Low harmonic generation
e) Fast, efficient, modular, and cost-effective solution

It reduces the time and resources required for project development. The relatively low number of components simplifies design, planning, and engineering tasks.SVC PLUS uses Voltage-Sourced Converter (VSC) technology based on Modular Multilevel Converter (MMC) design.

a) The MMC provides a nearly ideal sinusoidal-shaped waveform on the AC side. Therefore, there is only little – if any – need for high-frequency filtering and no need for low order harmonic filtering.
b) MMC allows for low switching frequencies, which reduces system losses.

MMC was first introduced by Marquart and Lesnicar in 2003 [2], and since then several research activities have been carried out focusing on the modulation [3-4], control [5-6], modeling [7-8], design [9-10] and protection [11-12]. Possibility of a common dc bus, simple voltage scaling by a series connection of identical cells, simple realization of redundancy, etc are its chief advantages. Above all, MMC offers a practical approach to construct a reliable and cheap STATCOM (called M-STATCOM) with increased number of levels, capable of eliminating interface transformers and replace them by cheap reactors to allow power exchange with the power system [13-14].

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In this paper, in section two, three phase MMC topology and its operating principle is studied. Also differenct modulation strategies for multilevel inverters are discussed.Section three describe direct current control strategy for the balancing of circulation current and capacitors voltage.Using instantaneous reactive theory,the expressions of the instantaneous active and reactive powers in the dq coordinate system are derived. Simulation results are discussed in section four. Section five concludes the paper.

2. Structure And Principle Of MMC

Figure 1 explains the structure of three-phase MMC. Six arms of MMC act as a controllable voltage source. Both the positive and negative arms compose a phase. Sub-modules are identical, evenly and serially connected in both arms and operate independently. A small inductor is included in each arm to limit fault currents. From Figure 1, it can be prove that the total voltages of two arms in a phase unit must be equal to the DC voltage (called principle of MMC), given by equation:

$$\left(u_{a1} + u_{a2}\right) = u_{dc} \tag{1}$$

With a flexible control of sub-modules, the desired sinusoidal voltage at the AC terminal can be achieved. Each Sub-Module consists of two IGBTs with anti-parallel diodes and a floating dc capacitor $\boldsymbol{V_{c0}}$ that form a typical bi-directional chopper, as shown in Figure 1~2.The terminal voltage of each sub-module can be either its capacitor voltage or zero, depending on the three switching states [15].

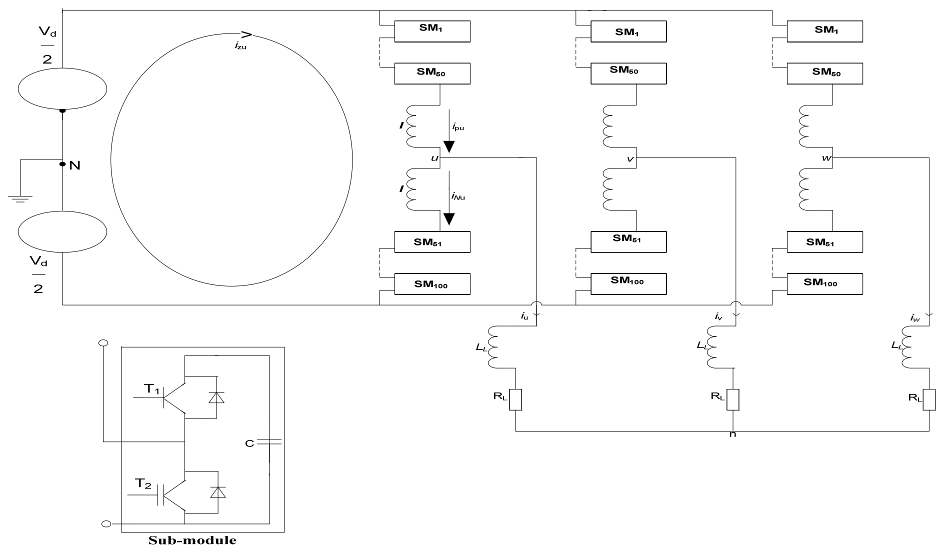


Figure 1. The structure of three-phase M-STATCOM along with Sub-Module

Figure 2. IGBT module (1200V/50A)

Several different sub-module topologies proposed in the literature.The most popular one is the half-bridge circuit including two power switches and a dc capacitor. The other three topologies are also based the half-bridge circuit, and the operating principles during normal conditions are nearly the same. The main difference of these four topologies is the performance during fault conditions [16].

The sub-module is a half-bridge sub-module outfitted with a by-pass thyristor and a by-pass vacuum switch.

2.1. Modulation Strategies for Multilevel Inverters

A number of modulation strategies are used in multilevel power conversion applications. They can generally be classified into three categories:

a) fundamental Frequency switching strategies
b) Space Vector PWM strategies
c) Carrier based PWM strategies

Of all the PWM methods for cascaded multilevel inverter, carrier based PWM methods and space vector methods are often used but when the number of output level is more than five, the space vector method will be very complicated with the increase of switching states. So the carrier based PWM method is preferred under this condition in multilevel inverters. This paper focuses on Level-shift sine pulse width modulation (LS-PWM) [17].

3. Direct Current Control Strategy

The direct current control compensation is a smooth, fast and accurate technique so widely use in industrial production as it is based on the reactive component of the instantaneous current for the main variable [18]. Direct current control scheme is implemented by varying modulation index in order to get variation in output voltage of STATCOM while keeping capacitor voltage constant. Combination of active and reactive current components using LS-PWM generates the reference value of the instantaneous current.

Assume that the three-phase symmetrical grid voltage as follows:

$$\begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} = \sqrt{2}V \begin{bmatrix} \cos(\omega t) \\ \cos(\omega t - \frac{2}{3}\Pi) \\ \cos(\omega t + \frac{2}{3}\Pi) \end{bmatrix} \tag{15}$$

Where, V is the RMS value of the voltage and ω is the angular frequency in rad/sec.Applying KVL to Figure 1 the average of three-phase system mathematical model is:

$$\frac{1}{2}L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{2}R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} - \frac{1}{2}\begin{bmatrix} u_{ma} \\ u_{mb} \\ u_{mc} \end{bmatrix} \tag{16}$$

Where, $u_{ma\sim mc}$ are the output voltage for phases a, b and c respectively. $i_{a\sim c}$ are M-STATCOM output currents for phases a, b and c respectively. By transferring the three phase grid-side voltages into the synchronous d-q coordinates as:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = T\begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} = \begin{bmatrix} \sqrt{3}v \\ 0 \end{bmatrix} \tag{17}$$

Where, T is the transformation matrix given by:

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2}{3}\Pi) & \cos(\omega t + \frac{2}{3}\Pi) \\ \sin(\omega t) & \sin(\omega t - \frac{2}{3}\Pi) & \sin(\omega t + \frac{2}{3}\Pi) \end{bmatrix} \tag{18}$$

According to the definition of instantaneous reactive theory[11],the expressions of the instantaneous active and reactive powers in the dq coordinate system are as follows:

$$\begin{cases} p = U_{sd} i_d = \sqrt{3} V i_d \\ q = U_{sd} i_q = \sqrt{3} V i_q \end{cases} \tag{19}$$

The instantaneous active power and reactive power exchange between the grid and M-STATCOM can be controlled by adjusting i_d and i_q, separately. When i_d is positive, M-STATCOM absorbs active power and the corresponding capacitors are charged. If i_d is negative, M-STATCOM releases active power to the grid and the corresponding capacitors are discharged. The M-STATCOM releases leading reactive power when i_q is positive, and lagging reactive power when i_q is negative.

4. Simulation Study

To prove that the M-STATCOM, based on proposed control strategy, provides the desired compensation effects a three phase, M-STATCOM of Figure 1 is simulated in PSCAD with 100Sub-modules per phase. Simulation and loads' parameters are summarized in Table 1.

Table 1. Simulation and load parameters

Name	parameters
Active power	200 MW
Sub-modules/phase	100
Reactive power	±10 MVar
Load inductance	15mH
Load resistance	0.1Ω
DC capacitance	3nF
3-ph source voltage	10kv
Carrier freq.	5kHz
Dc resistance	2.8Ω
Dc voltage	±40kv
IGBT module	1200V/50A
Amplitude modu rate	0.95

From Figure 3~5, after compare and contrast only Level-shift sine pulse width modulation (LS-PWM) is found more appropriate as it is providing an even power distribution among the cells as well as it decreases power losses and improves efficiency so, it can be used to control the converter. It uses two reversed sine waves to compare with some triangular waves who has the same amplitude and phase but the vertical position shifts a level one by one that is shown in Figure 6(a/b) while Figure 6(c) depicts the equivalent modulated signal.

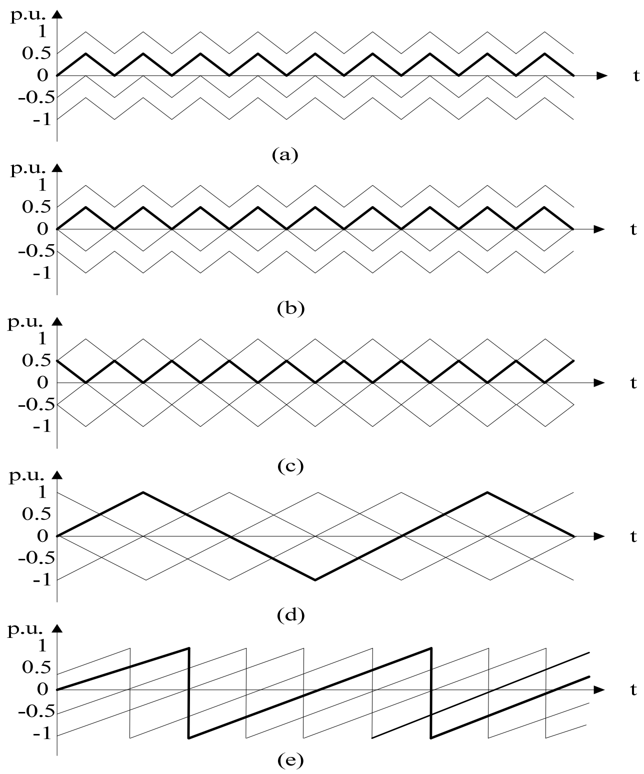


Figure 3. Multi-carrier modulation waveform (a) PD (b) POD (c) APOD (d) CPS, (e) SPS

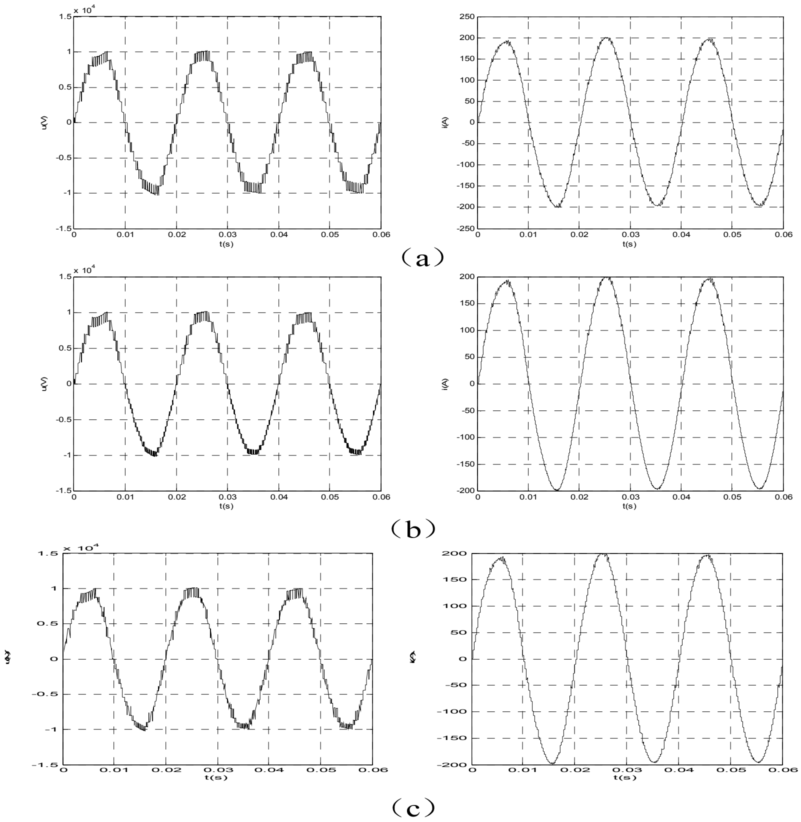
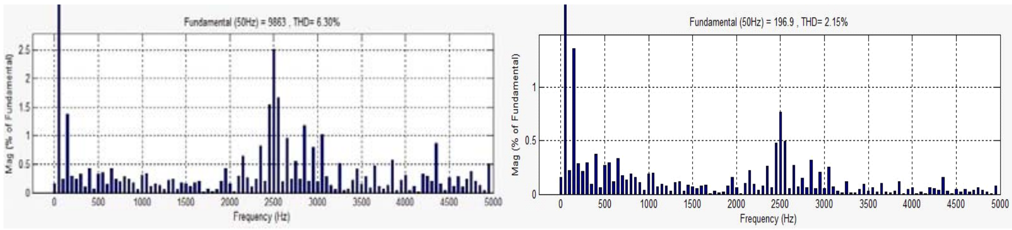
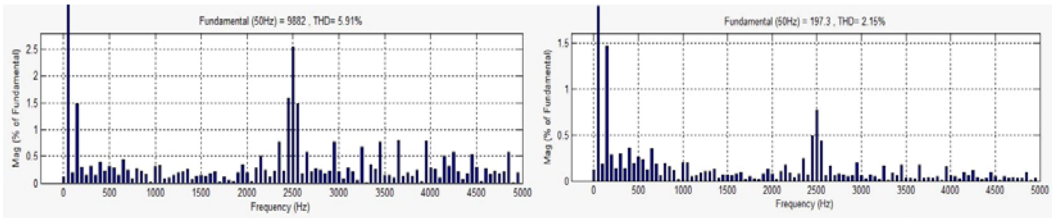


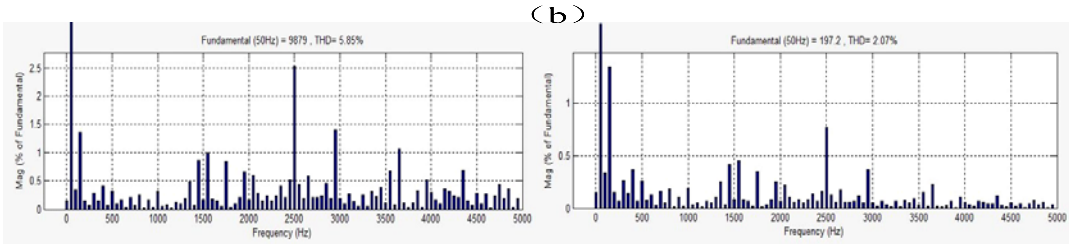
Figure 4. PD, POD, APOD corresponding output voltage and current



(a)



(b)



(c)

Figure 5. PD, POD, APOD corresponding output voltage and current harmonic content

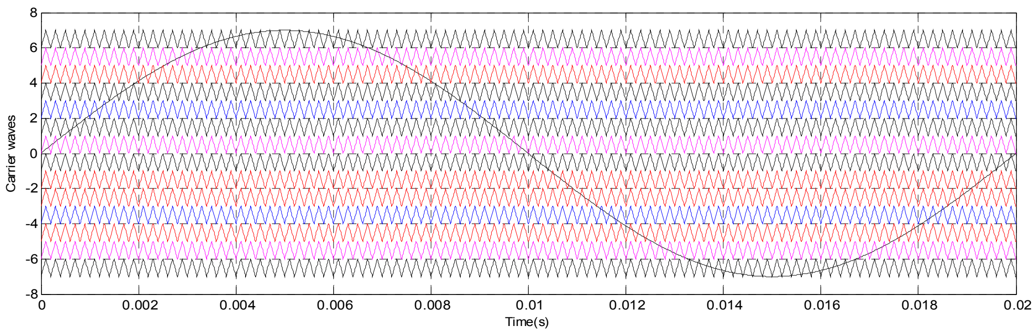


Figure 6(a). Upper carrier and reference signal

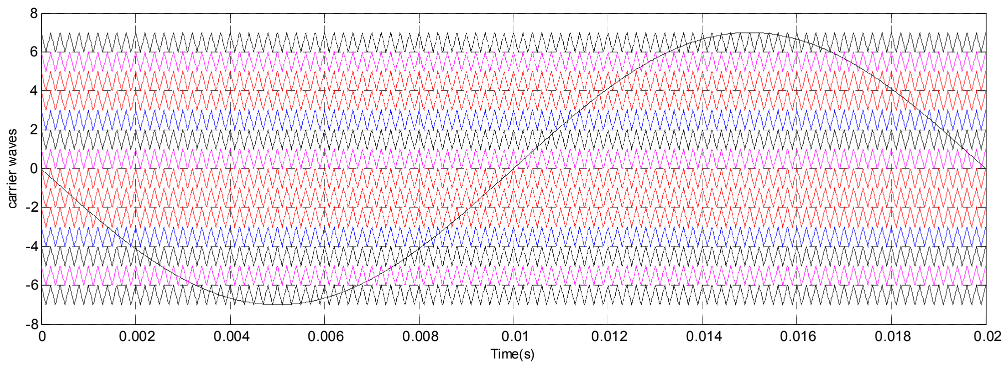


Figure 6(b). Lower carrier and reference signal

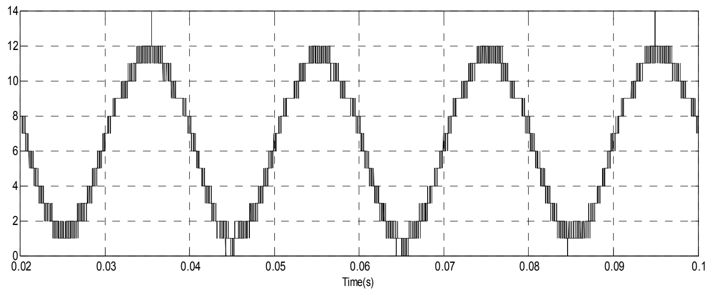


Figure 6(c). Equivalent modulated signal

In Figure 7, single phases of voltage and current at PCC are examined before and after 0.1s, without the M-STATCOM action. Before 0.1s, as the load is inductive so the current lags the voltage by a certain angle. Due to the large inductive reactive power the voltage drop is 5% of the rated voltage which is making power quality poor. After 0.1s, as the load is capacitive the current leads the voltage by a certain angle. Due to excessive capacitive reactive power, voltage rises 5% higher than the rated voltage, which is also unwanted situation. So, in both the cases for the stable and efficient grid operation M-STATCOM is used.

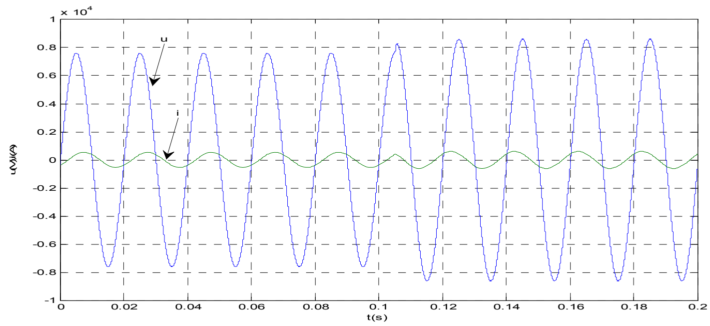


Figure 7. Single phases of voltage and current (without the M-STACOM action)

In Figure 8, single phases of voltage and current at PCC with M-STATCOM action is shown. After the M-STATCOM is put into operation, As can be seen from the Figure 8, either before or after the 0.1s, current and voltage are substantially in phase and the load became equivalent to a resistive load.Before 0.1s, M-STATCOM operated in the capacitive mode, generated capacitive reactive power in order to compensate the inductive reactive power, Thus, M-STATCOM improved the power factor and reduced the current flowing through the lines. Due to the pure active current, the line losses and voltage drops are least and hence the voltage level at PCC is improved. After 0.1s, M-STATCOM operated in the inductive mode so it absorbed inductive reactive power of the charging power cable, and hence reduced the network voltage level.

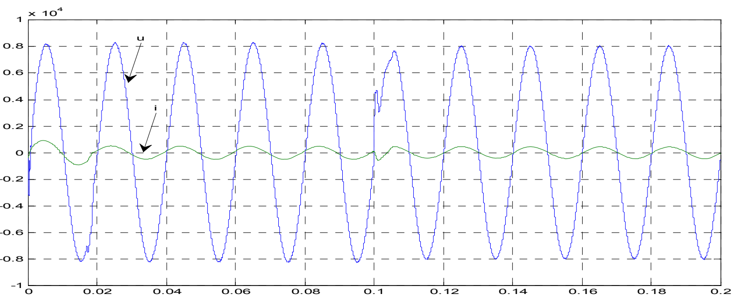
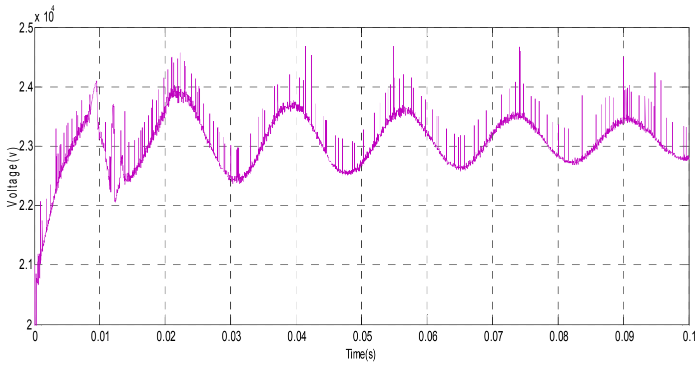
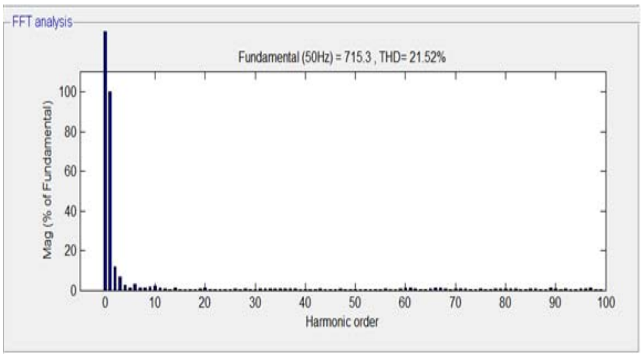


Figure 8. A single phase of voltage and current at PCC with M-STATCOM action

M-STATCOM DC bus voltage and its FFT analysis shown in Figure 9. As can be seen from Figure 9(a), the DC bus voltage fluctuation is small and has the double frequency viz. 100HZ harmonic waves, with least harmonic components (THD=47.94%). This proves that the DC bus voltage regulator control strategy is good.



(a) M-STATCOM DC bus voltage



(b) FFT analyses of M-STATCOM DC bus voltage

Figure 9. M-STATCOM DC bus voltage and harmonic content

The M-STATCOM'S capacitor modules voltages for upper and lower bridges are shown in Figure 10. As it can be seen from Figure 10 that the capacitors' voltage fluctuations both for lower and upper arm are almost same and of very small value around 0.1%.Thus,it verifies that the capacitance voltage control strategy is successful.

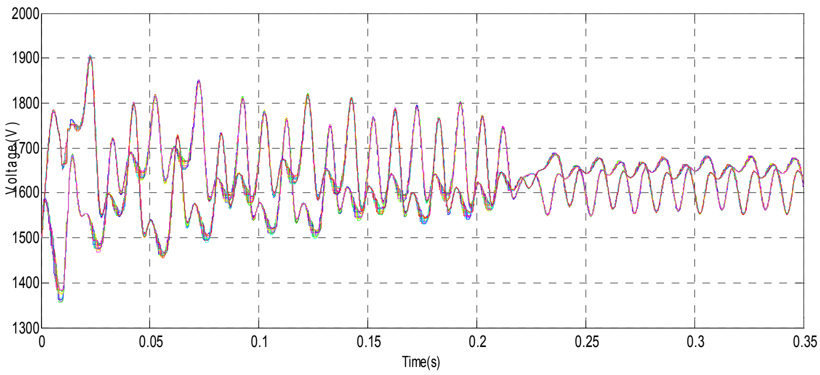


Figure 10. Capacitor voltages of all the sub-modules in a phase

5. Conclusion

The computer simulation in the PSCAD environment confirmed the proper operation of the three-phase SVC plus.The following conclusions can be drawn:

1) The novel direct current control strategy improved the traditional capacitor voltage balance algorithm. The circulating current ripples found lower.
2) Level-shift sine pulse width modulation (LS-PWM) is found more appropriate due to least total harmonic distortions(THD).It provided an even power distribution among the cells as well as decreased the power losses and improved efficiency. With this modulation scheme converter achieved more levels so it is found feasible to control the converter.
3) Simulation of large number of sub-modules in PSCAD environment is faster as compared to the MATLAB/SIMULINK environment.
4) SVC PLUS is an innovative and universally applicable solution for grid enhancement.It improved dynamic stability and power quality of power systems in a new, highly economical manner.

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